Inflation and Gravitational Waves

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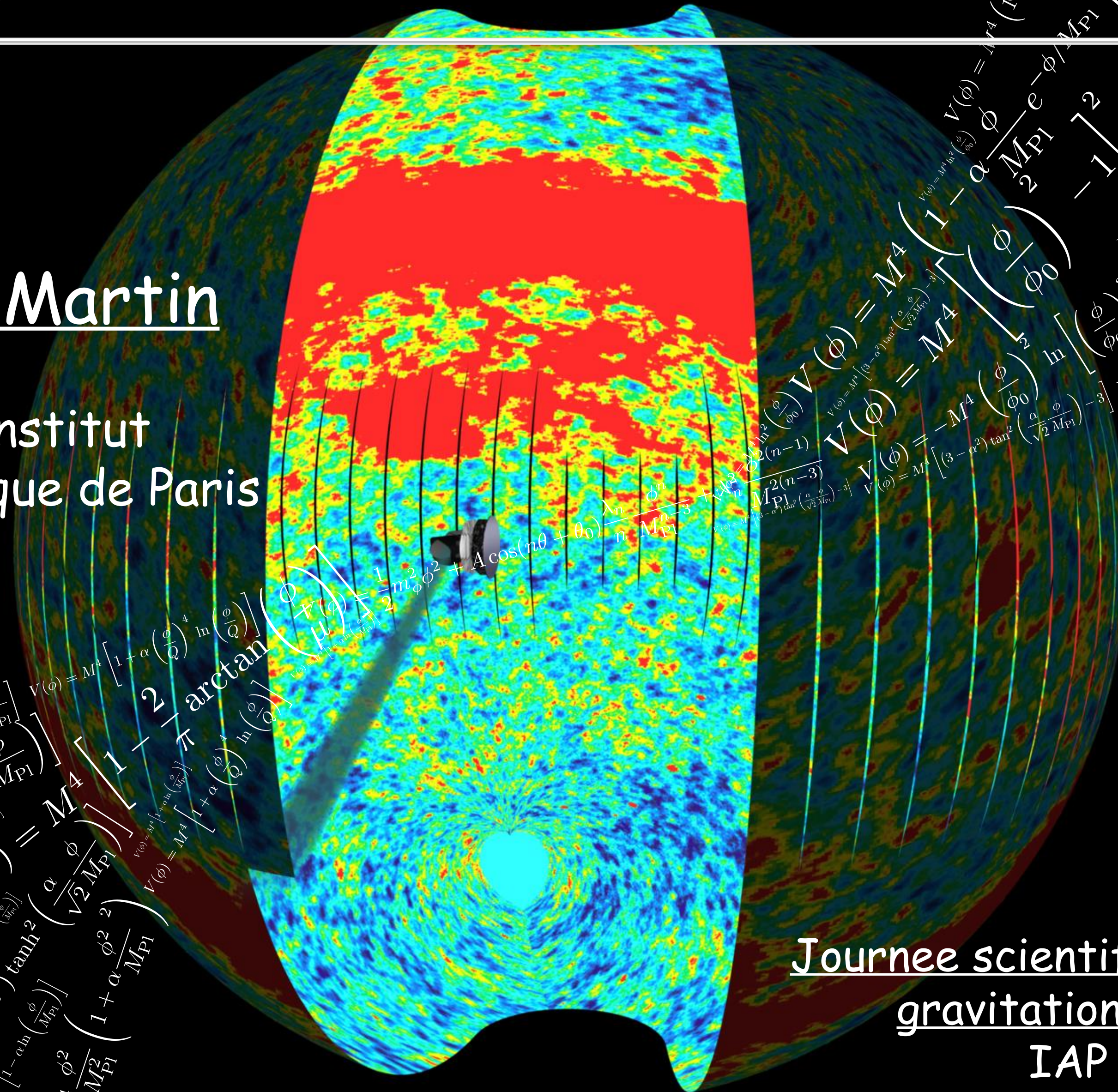

Journee scientifique ondes gravitationnelles
IAP
January 27, 2017

Outline

- Inflation after Planck 2013 & 2015: Theoretical and observational status
- Gravity waves produced during the slow-roll phase
- Gravity waves produced at the end of inflation (preheating)
- Conclusions.

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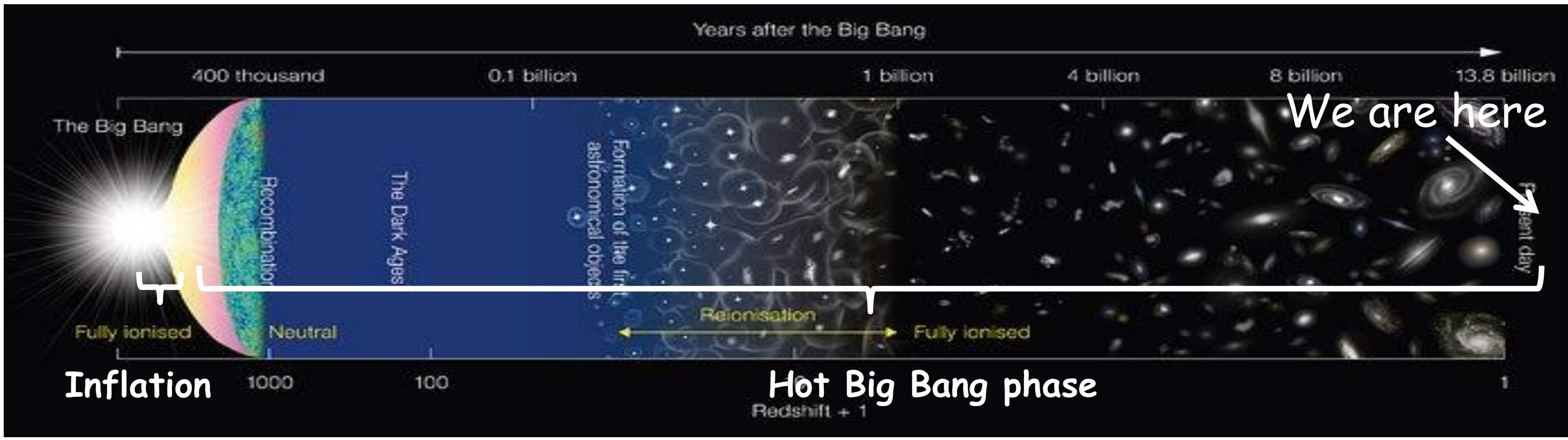
Inflation is a phase of <u>accelerated, quasi exponential, expansion</u> taking place in the very <u>early Universe</u>, before the standard Hot Big Bang epoch



$$a \propto \exp(Ht) \longrightarrow \frac{\ddot{a}}{a} = H^2 > 0$$

Inflation solves the puzzles of the standard model of Cosmology

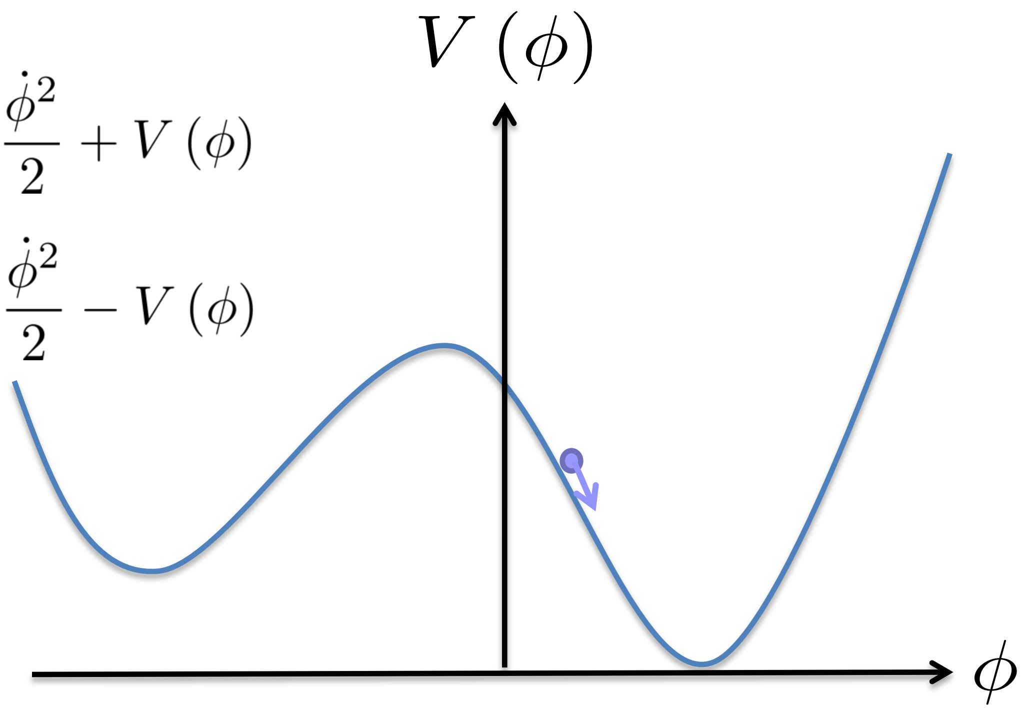
Inflation in brief

Inflation is (usually) realized with one (or many) scalar field(s)

$$\frac{\ddot{a}}{a} = -\frac{1}{6M_{\rm Pl}^2}\left(\rho + 3p\right)$$

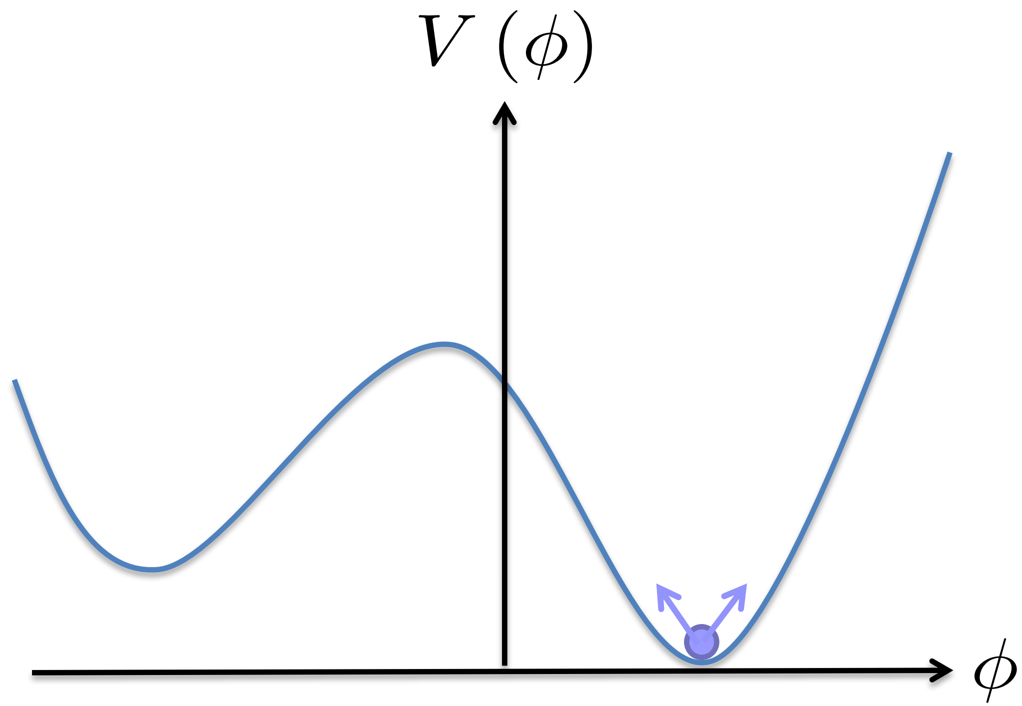
$$\rho = \frac{\dot{\phi}^2}{2} + V\left(\phi\right)$$

$$p = \frac{\dot{\phi}^2}{2} - V\left(\phi\right)$$



If the scalar field moves slowly (the potential is flat), then pressure is negative which, in the context of GR, means accelerated expansion and, hence, inflation takes place.

Inflation (usually) stops when the field reaches the bottom of the potential



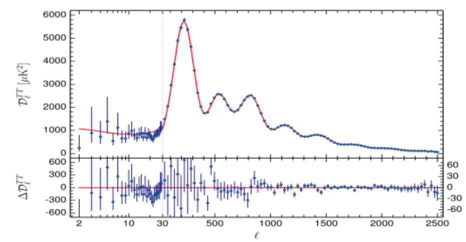
The field oscillates, decays and the decay products thermalize …Then the radiation dominated era starts …

The status of inflation

Single field slow-roll models, with minimal kinetic terms, are perfectly compatible with all astrophysical data (in particular CMB Planck data)

- Universe spatially flat $\Omega_{\mathcal{K}} = -0.040^{+0.038}_{-0.041}$

- Phase coherence

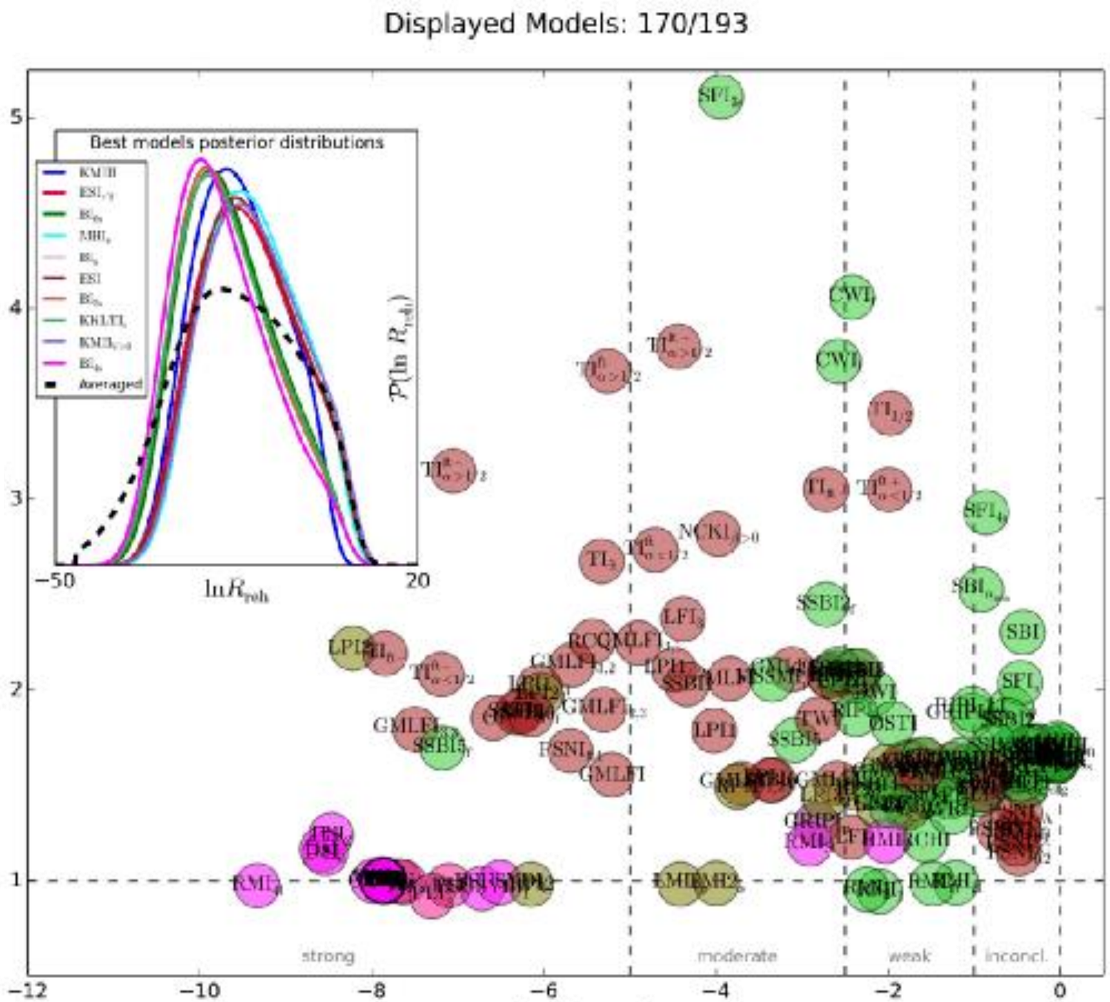


- Adiabatic perturbations $\alpha_{\mathcal{RR}}^{(2,2500)} \in [0.985, 0.999]$

- Gaussian perturbations $f_{\mathrm{NL}}^{\mathrm{loc}} = 0.8 \pm 5$

- Almost scale invariant power spectrum $n_{\mathrm{S}} = 0.9645 \pm 0.0049$

- Background of quantum gravitational waves??



Constraints on reheating

Model performance $\ln(\mathcal{E}/\mathcal{E}_{\rm best})$

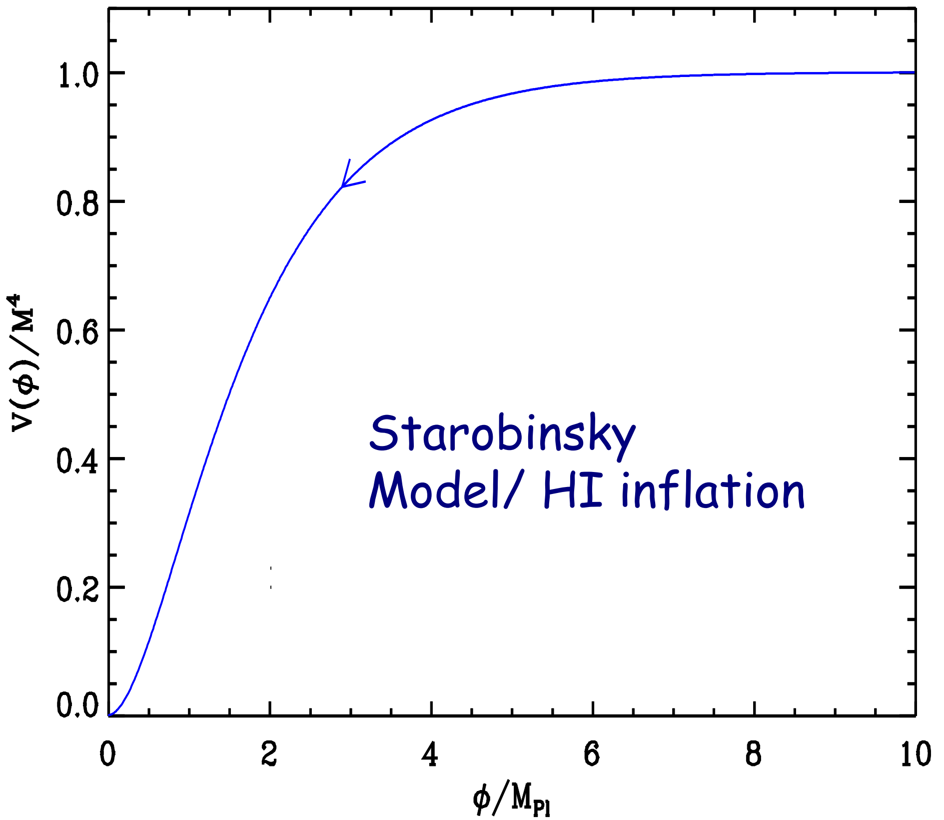
No constraint on reheating

J. Martin, C. Ringeval & V. Vennin, Phys. Dark Univ. 5-6 (2014), 75, arXiv:1303.3787

J. Martin, C. Ringeval & V. Vennin, Phys. Rev. Lett. 114 (2015), 081303, arXiv:1410.7958

Plateau inflationary models are the winners!

J. Martin, C. Ringeval R. Trotta & V. Vennin, JCAP1403 (2014), 039, arXiv:1312.3529



$$V(\phi) = M^4 \left(1 - \mathrm{e}^{-\sqrt{2/3}\phi/M_{\mathrm{Pl}}}\right)^2$$

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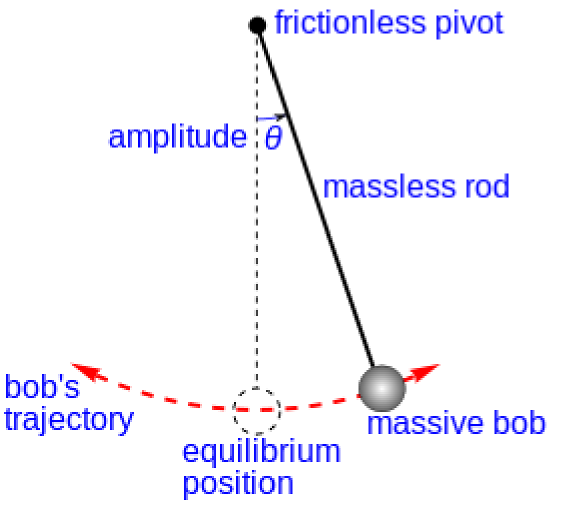
According to inflation, the source of the inflationary GW are the unavoidable quantum fluctuations of the metric perturbations

Classical mechanics

$$\langle E \rangle = 0$$

Quantum mechanics:

$$\langle E \rangle = \frac{\hbar \omega}{2}$$



These quantum fluctuations are amplified during inflation and give rise to a background of GW today (NB, same mechanism for the origin of LSS and CMB anisotropies)

Inflationary predictions: the two-point correlation function

$$\mathcal{P}_\zeta = \frac{H_*^2}{\pi \epsilon_{1*} m_{\rm Pl}^2}\left[1 - 2\left(C+1\right)\epsilon_{1*} - C\epsilon_{2*} - \left(2\epsilon_{1*}+\epsilon_{2*}\right)\ln\left(\frac{k}{k_{\rm P}}\right)\right]$$

$$\mathcal{P}_h = \frac{16 H_*^2}{\pi m_{\rm Pl}^2}\left[1 - 2\left(C+1\right)\epsilon_{1*} - 2\epsilon_{1*}\ln\left(\frac{k}{k_{\rm P}}\right)\right]$$

The power spectra are scale-invariant plus logarithmic corrections the amplitude of which depend on the sr parameters, ie on the microphysics of inflation

C~ -0.7

*= at Hubble radius crossing

$$\epsilon_1 \simeq \frac{1}{2M_{\rm Pl}^2}\left(\frac{V_\phi}{V}\right)^2$$

$$\epsilon_2 \simeq \frac{2}{M_{\rm Pl}^2}\left[\left(\frac{V_\phi}{V}\right)^2 - \frac{V_{\phi\phi}}{V}\right]$$

Consistency relation:

$$r = \frac{T}{S} \equiv \frac{\mathcal{P}_h}{\mathcal{P}_\zeta} = 16\epsilon_{1*} = -8n_{\rm T}$$

Gravitational waves are subdominant

The spectral indices are given by

$$n_{\rm S} - 1 \equiv \frac{{\rm d}\ln \mathcal{P}_\zeta}{{\rm d}\ln k}\,, \quad n_{\rm T} \equiv \frac{{\rm d}\ln \mathcal{P}_h}{{\rm d}\ln k}$$

$$n_{\rm S} = -2\epsilon_{1*} - \epsilon_{2*} \quad n_{\rm T} = -2\epsilon_{1*}$$

Detection of tensor modes

- Check the remaining key prediction of inflation

Planck 2015 + Bicep/Keck: $r < 0.08 \quad 95\%\mathrm{CL}$

- Final proof of vanilla inflation: consistency check (but needs n_T)
- Energy scale of inflation
- Measurement of the first derivative of the potential
- Field excursion
- Greatly improve model selection
- Greatly improve constraints on reheating

Detecting gravitational waves by measuring B-modes

- Ground based experiments: BICEP3 & Keck, SPTPol, ACTPol etc …

- Balloon borne experiments: EBEX, SPIDER, PIPER etc …

- Space Missions: CORE (Europe), EPIC, PIXIE (US), LiteBIRD (Japan)

Detecting gravitational waves by measuring B-modes

- Next generation of CMB mission with a target: $r \sim 10^{-4}$
  [Starobinsky model, $r \sim (2\text{-}4) \times 10^{-3}$, Planckian excursion $r \sim 10^{-3}$]

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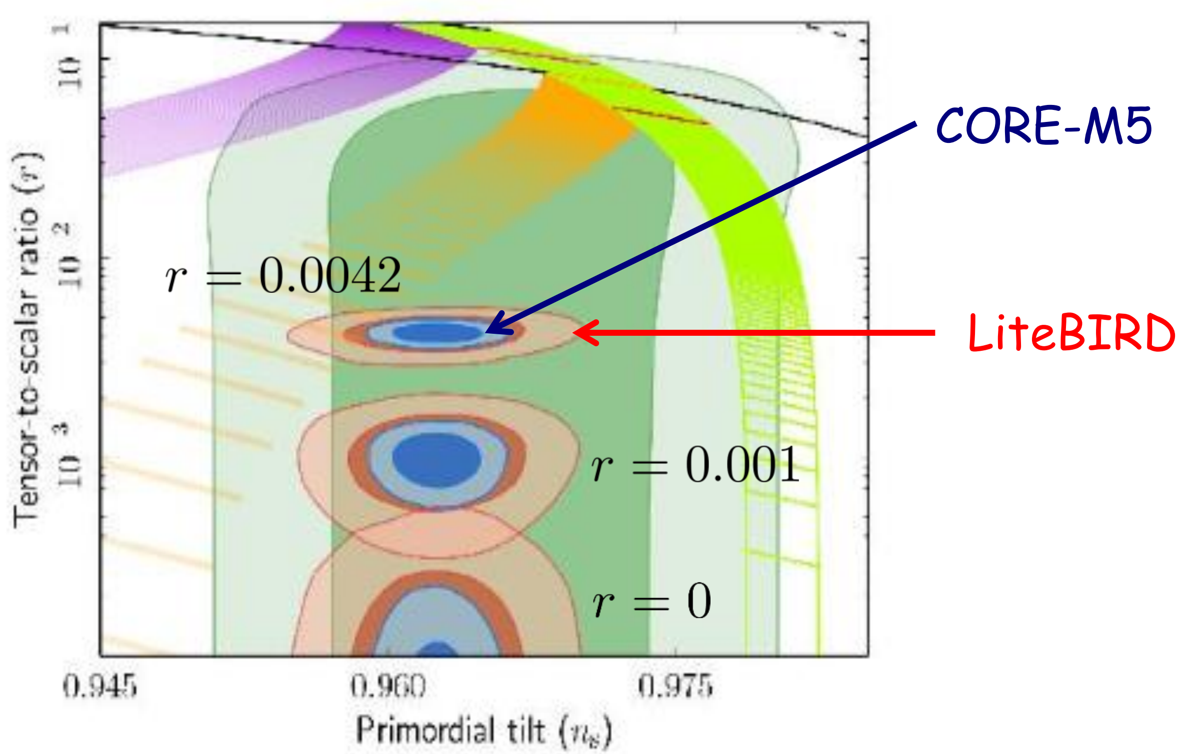
- Forecast in the (ns, r) space



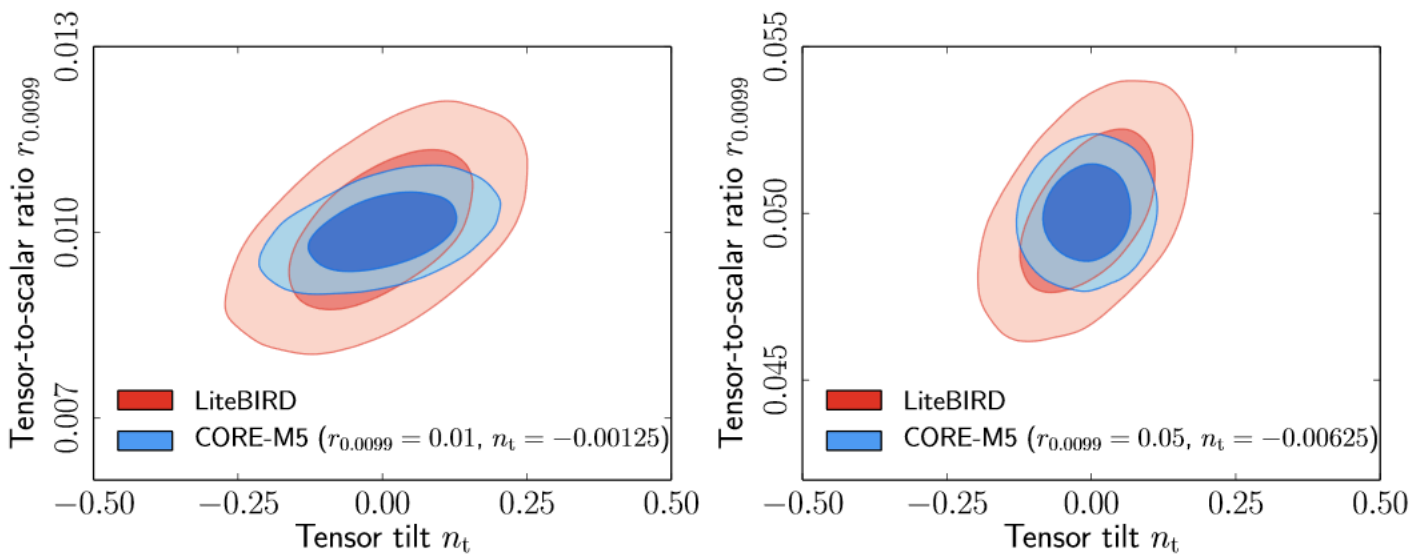
Exploring Cosmic Origins with CORE: Inflation arXiv:1612.08270

Detecting gravitational waves by measuring B-modes

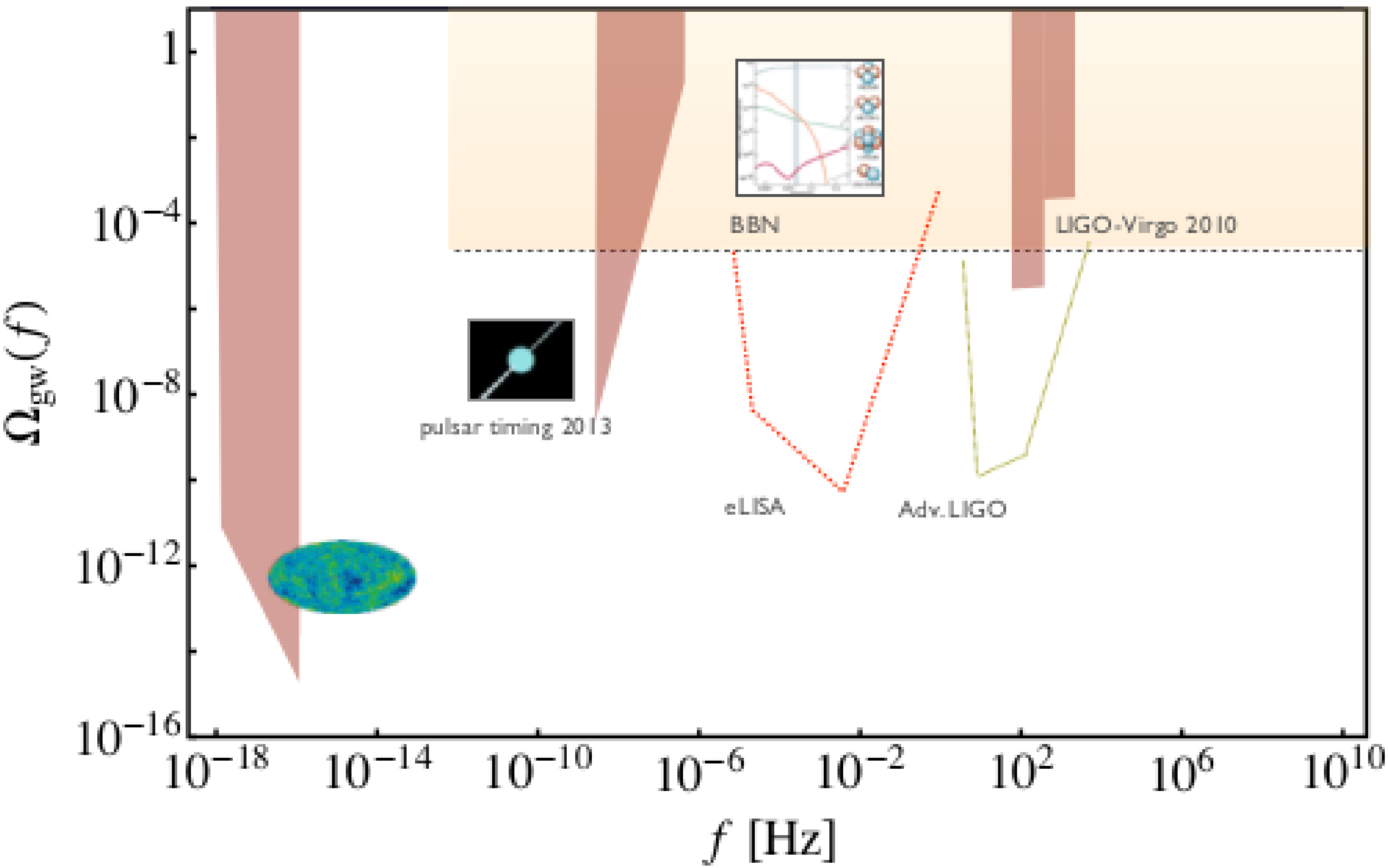
- Next generation of CMB mission with a target: r ~ 10^{-4}
  [Starobinsky model, r ~ (2-4) x10^{-3}, Planckian excursion r~ 10^{-3}]

- Forecast in the (ns, r) space

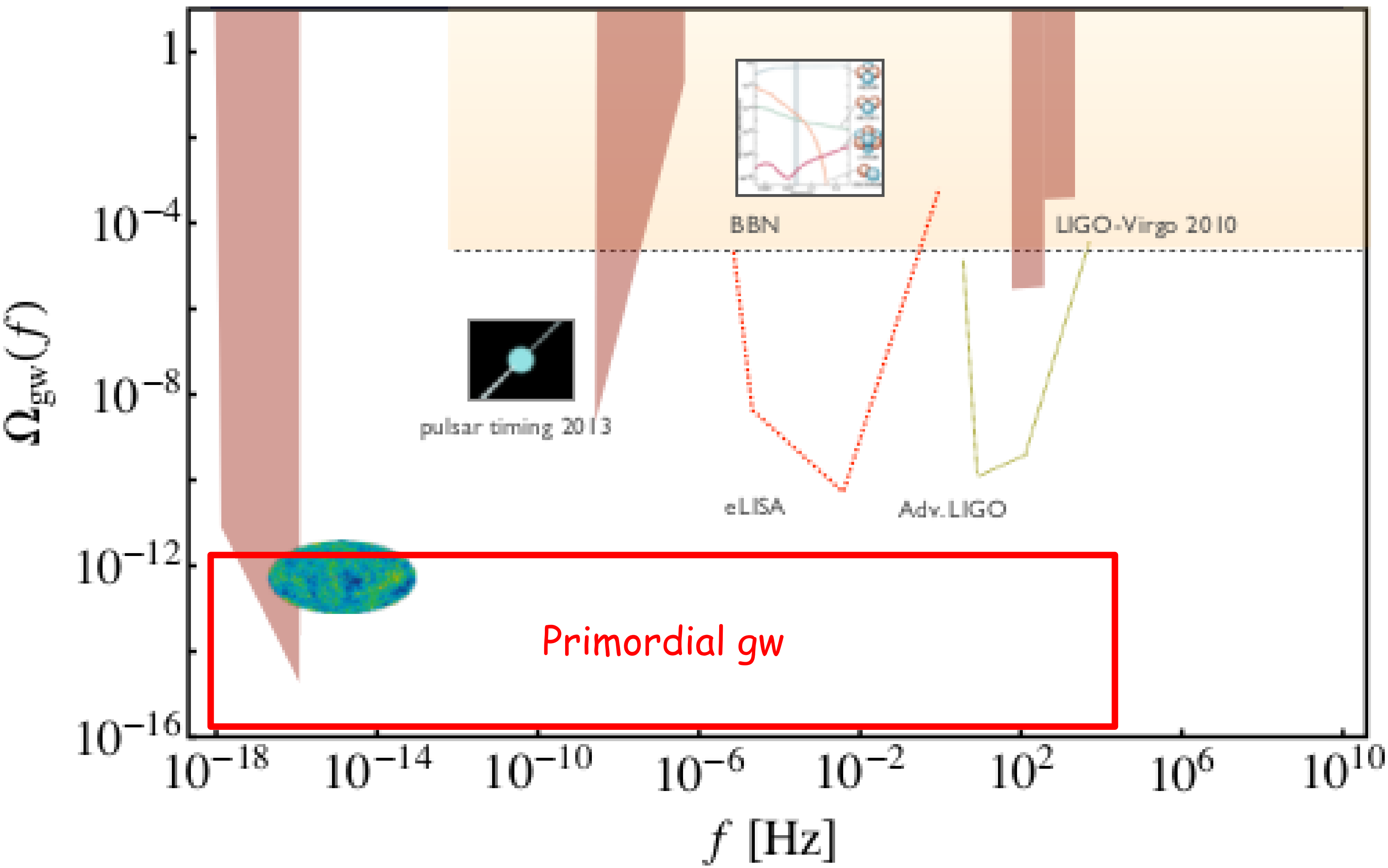
- Checking the consistency relation $n_T = -r/8$?

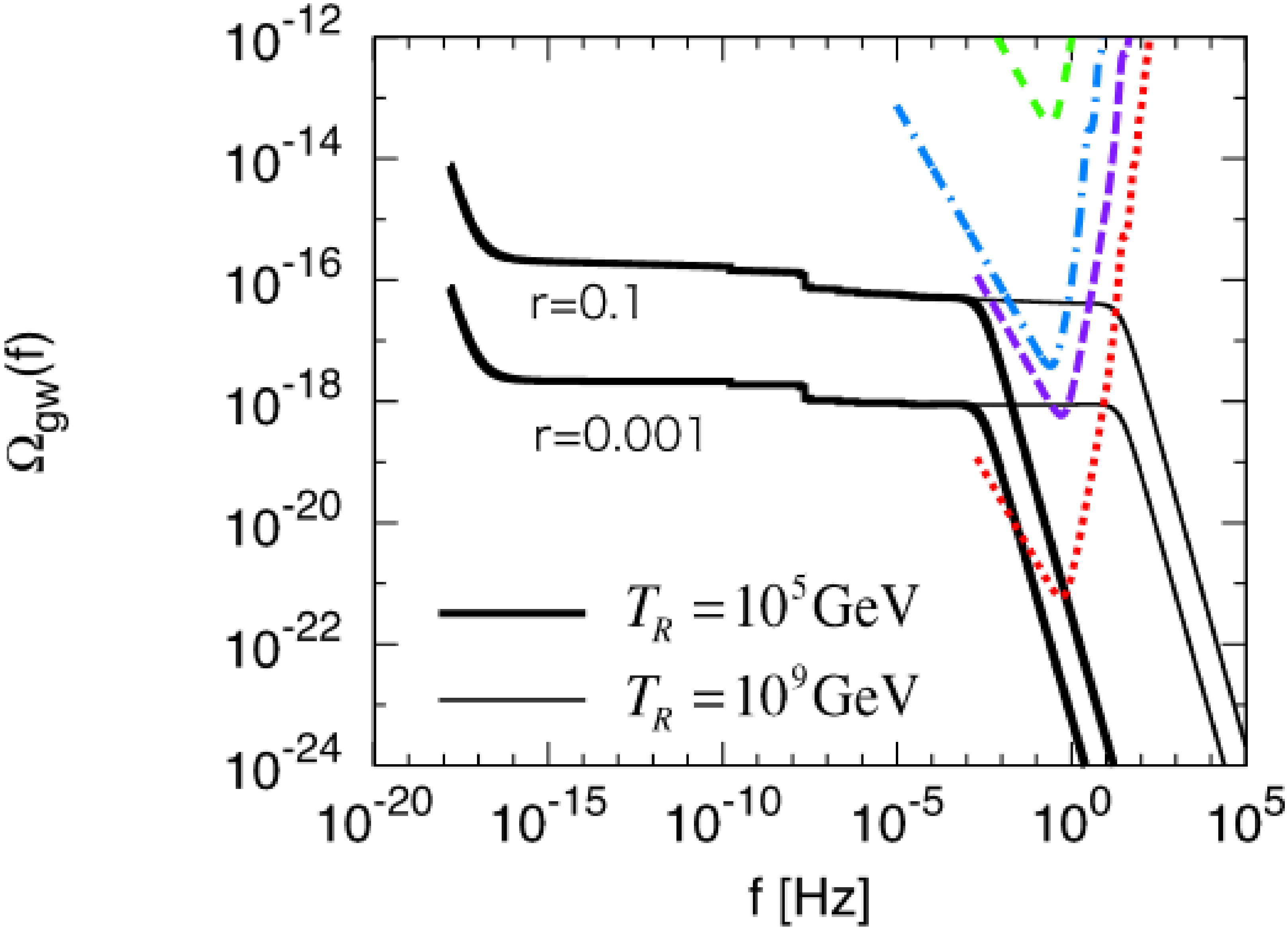


Direct detection?



Direct detection?





K. Nakayama, S. Saito, Y. Suwa. J. Yokoyama, arXiv:0804.1827

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After the end of inflation, the coupling between the inflaton field and the "rest of the world" plays a crucial role

$$\mathcal{L} = -\frac{1}{2}\left(\partial\phi\right)^2 - V\left(\phi\right) - \frac{1}{2}\left(\partial\chi\right)^2 - \underbrace{\frac{1}{2}g^2\phi^2\chi^2}_{\text{Interaction term}}$$

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Interaction term

$$\downarrow$$

$$\ddot{\chi}_{\mathbf{k}} + 3H\dot{\chi}_{\mathbf{k}} + \left[\frac{k^2}{a^2} + g^2\phi^2(t)\right]\chi_{\mathbf{k}} = 0$$

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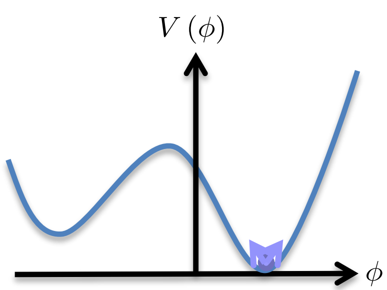


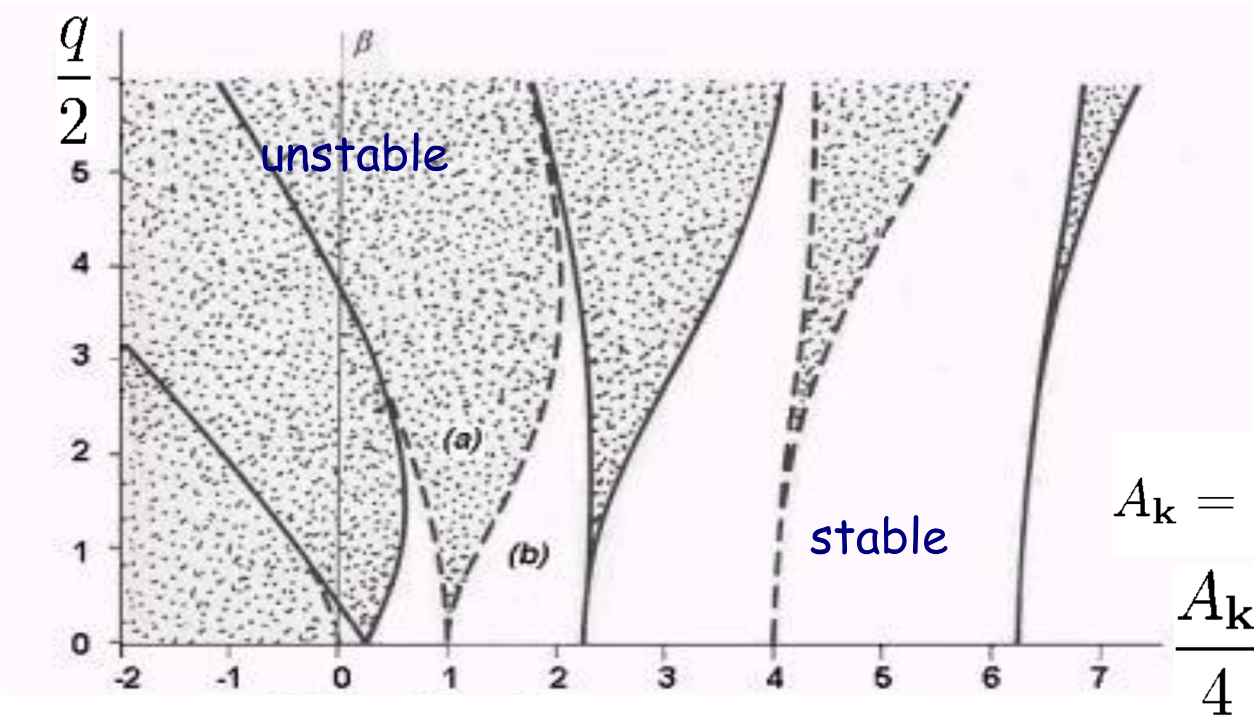
$$\phi(t) = \Phi(t)\sin(mt)$$

$$\frac{\mathrm{d}^2 X_{\mathbf{k}}}{\mathrm{d}z^2} + \left[A_{\mathbf{k}} - 2q\cos(2z)\right]X_{\mathbf{k}} = 0$$

$$\frac{\mathrm{d}^2 X_{\mathbf{k}}}{\mathrm{d}z^2} + \left[A_{\mathbf{k}} - 2q\cos(2z)\right] X_{\mathbf{k}} = 0$$

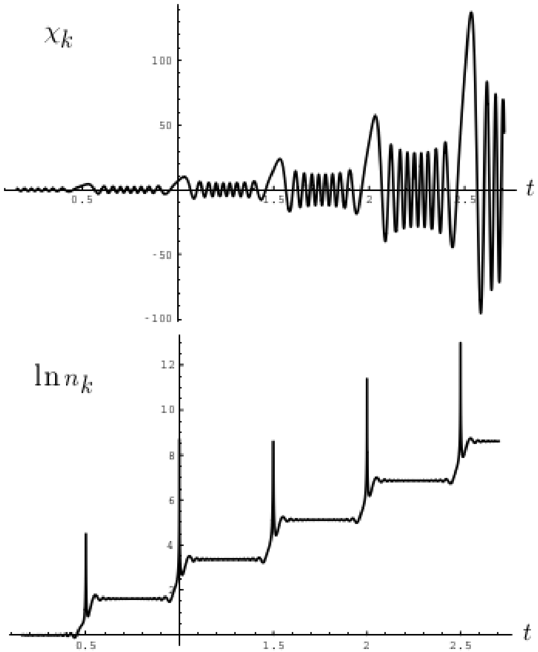
In the resonance band, one has exponential production of particles

$$q = \frac{g^2\Phi^2}{4m^2}$$



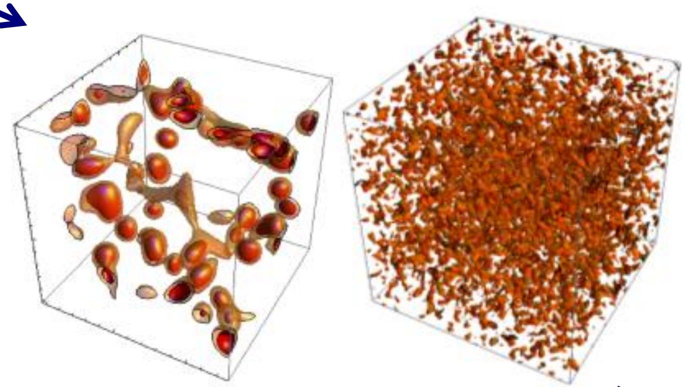
$$A_{\mathbf{k}} = \frac{k^2}{m^2 a^2} + 2q$$

Mathieu Instability Card



L. Kofman, A. Linde, A. Starobinsky, hep-th/9405187

Early structure formation
"bubbly stage"



Explosive particle production

G. Felder, L. Kofman, hep-ph/0011160

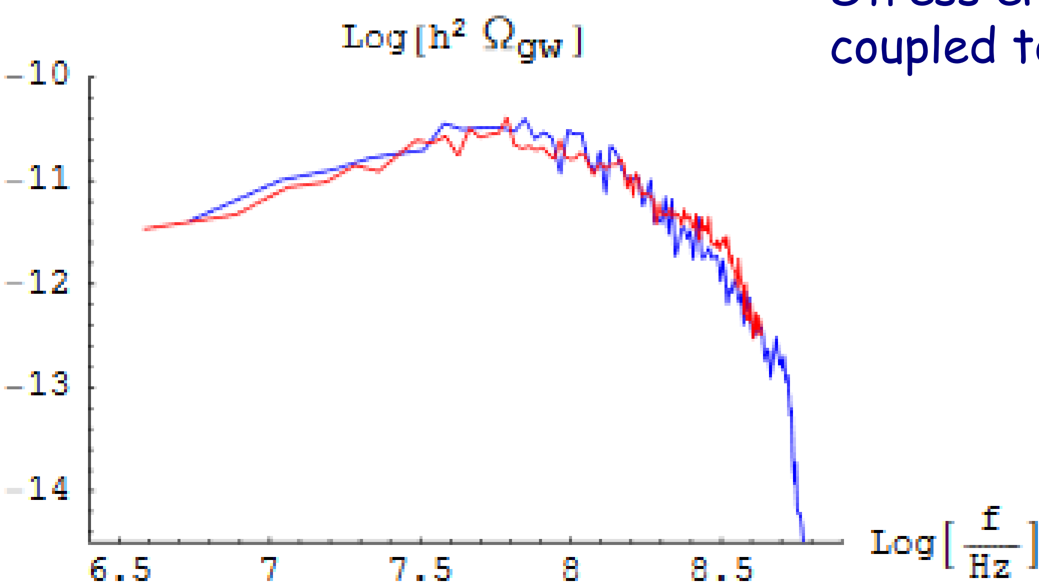
Thermalization

G. Felder, J. Garcia-Bellido, P. Green, L. Kofman, A. Linde, I Tkachev, hep-ph/0012142

The inhomogeneities produced during preheating can in turn source gravitational waves

$$h''_{ij} + 2\frac{a'}{a}h'_{ij} - \nabla^2 h_{ij} = \frac{2}{M^2_{\rm Pl}} a^2 T^{\rm TT}_{ij}$$

Stress energy tensor of the field coupled to the inflaton



R. Easther, E. Lim, astro-ph/0601617

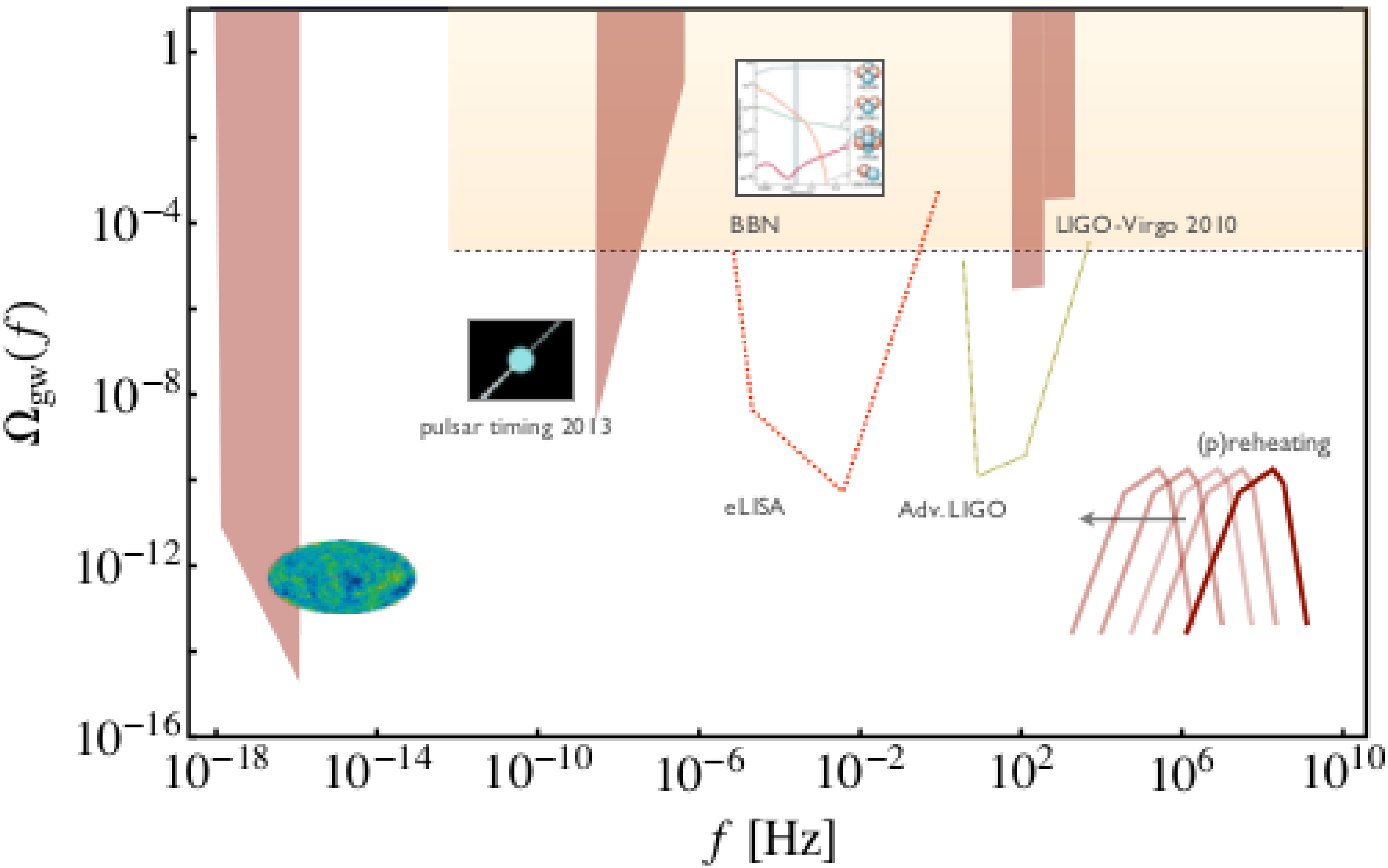
J. F. Dufaux, A. Bergman, G. Felder, L. Kofman, J. P. Uzan, arXiv:0707.0875

See also

K. Jedamzik, M. Lemoine, J. Martin, arXiv:1002.3278

K.Jedamzik, M. Lemoine, J. Martin, arXiv:1002.3039

Preheating



1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
$\Omega_{gw}(f)$
BBN
LIGO-Virgo 2010
pulsar timing 2013
(p)reheating
eLISA
Adv.LIGO
10^{-18}
10^{-14}
10^{-10}
10^{-6}
10^{-2}
10^{2}
10^{6}
10^{10}
f [Hz]

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Recap

- There two types of gravity waves produced during inflation

- Detecting the B-modes is a way to detect the GW produced during the slow-roll phase

- Direct detection of the GW produced during the slow-roll phase seems very hard (the situation can maybe changed if one considers more complicated models of inflation, eg pseudo inflation L. Sorbo, arXiv:1101.1525)

- Direct detection of GW produced during preheating is maybe feasible; The result is strongly model and parameter dependent.